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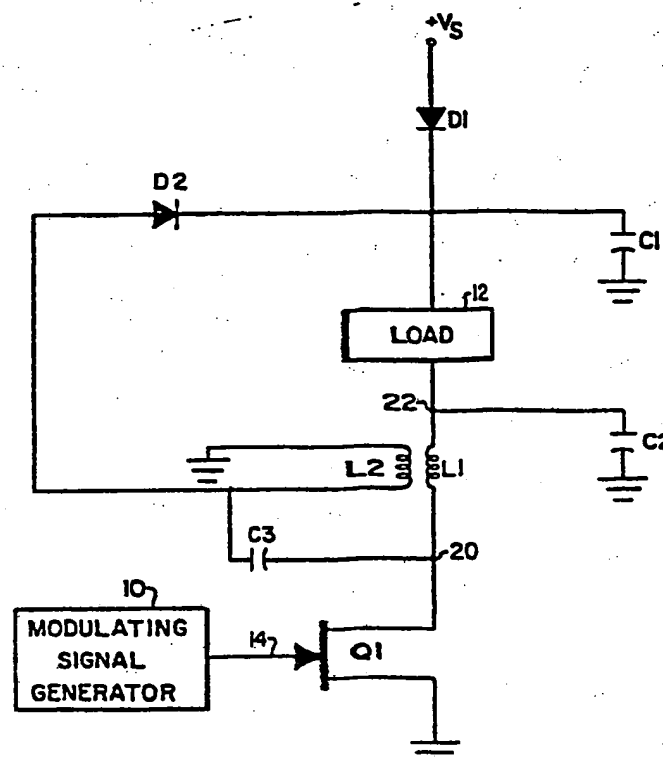


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(54) Title: EFFICIENT CURRENT MODULATOR USEFUL WITH INDUCTIVE LOADS**(57) Abstract**

A current modulator for modulating the current flowing through a load (12) from a DC power supply (V_s) to circuit ground. A switching device (Q1) is connected between the load (12) and circuit ground for varying the current through the load (12) in response to a modulating signal (14) applied to the switching device (Q1). A first inductance coil (L1) is connected between the switching device (Q1) and the load (12). A second inductance coil (L2) is mutually coupled to the first coil (L1) for receiving energy induced in the first coil (L1) by the current variations. The second coil (L2) is conductively isolated from the first coil (L1). A diode (D2) is connected between the second coil (L2) and the power supply side of the load (12) for transferring the received energy back to the power supply side of the load (12).



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"EFFICIENT CURRENT MODULATOR USEFUL WITH INDUCTIVE LOADS"

BACKGROUND OF THE INVENTION

5 The present invention pertains to current modulators and is particularly directed to enhancing the utility and improving the efficiency of current modulators that are used for modulating the current flowing through a load from a DC power supply to circuit ground.

10 In prior art current modulators of this type, a switching device is connected between the load and circuit ground for varying the current through the load in response to a modulating signal applied to the switching device. An overshoot clipping diode is connected between the switching device and the power supply side of the load for protecting the load and the
15 switching device and the power supply side of the load for protecting the load and the switching device from excessively high currents.

20 Such prior art current modulator cannot be operated to produce an alternating current through an inductive load. Because the voltage at the switching device side of the load would exceed the power supply voltage during each half cycle, whereby the diode would become forward biased and effectively cause a short circuit across the load.

SUMMARY OF THE INVENTION

25 The present invention provides an efficient current modulator that is useful with inductive loads.

-2-

The present invention is a current modulator for modulating the current flowing through a load from a DC power supply to circuit ground, including a switching device connected between the load and circuit ground for varying the current through the load in response to a modulating signal applied to the switching device; a first inductance coil connected between the switching device and the load; a second inductance coil mutually coupled to the first coil for receiving energy induced in the first coil by the current variations; and a diode coupled between the second coil and the power supply side of the load for transferring the received energy to the power supply side of the load. The second inductance coil is conductively isolated from the first inductance coil. As a result when the diode becomes forward biased for transferring energy to the power supply side of the load, it nevertheless does not cause a short circuit across an inductive load.

Because energy is returned to the power supply side of the load by the diode, the current modulator of the present invention is more efficient.

The efficiency of the current modulator is further increased by using a high frequency switching device. Less power is lost in a high frequency switching device because it has shorter turn-on time.

The efficiency of the current modulator is still further enhanced by providing that the mutually coupled inductance coils have an air core. The combination of air core inductance coils and switching at a high frequency reduces heat loss in the inductance coils.

Additional features of the present invention are described in the description of the preferred embodiments.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a combination block and schematic circuit diagram of a preferred embodiment of the current modulator of the present invention.

Figure 2 is a schematic circuit diagram of the modulating signal generator included in the current modulator of Figure 1.

Figures 3A through 3E illustrate waveforms of signals produced in the modulating signal generator of Figure 2.

Figure 4 is a combination block and schematic circuit diagram of another preferred embodiment of the current modulator of the present invention.

Figure 5 is a schematic circuit diagram of the modulating signal generator included in the current modulator of Figure 4.

Figures 6A through 6F illustrate waveforms of signals produced in the modulating signal generator of Figure 5.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to Figure 1, a preferred embodiment of the current modulator of the present invention includes a high frequency switching device Q1, a first inductance coil L1, a second inductance coil L2, two diodes D1 and D2, three capacitances C1, C2 and C3 and a modulating signal generator 10. The switching device Q1 is a VMOS FET power transistor which is capable of switching at high frequencies. The transistor Q1 is connected between a load 12 and circuit ground for varying the current through the load 12 in response to a modulating signal applied on line 14 to the gate of the transistor Q1 from the modulating signal generator 10. A DC power supply terminal V_s is coupled to the other side of the load 12 by a protective diode D1. The load 12 is isolated from circuit ground by the capacitances C1 and C2.

The first inductance coil L1 is connected between the transistor Q1 and the load L2. The second inductance coil L2 is mutually coupled to the first inductance coil L1 for receiving energy that is induced in the first inductance coil L1 by variations in the current through the load L2. The first and second inductances L1, L2 are tightly wound on an air-filled core by a bifilar, or preferably a coaxial winding.

The first and second inductances L1, L2 are conductively isolated from each other, i.e. there is no DC current path between the coils L1 and L2. However, the coils L1 and L2 are coupled by the capacitance C3 to minimize any problems that could arise due to poor mutual coupling between the coils L1 and L2.

The diode D2 is connected between the second inductance coil L2 and the power supply side of the load L2 for transferring the received energy from the second coil L2 to the power supply side of the load L2.

The modulating signal generator 10 is adopted for applying a high frequency pulsed modulating signal to the gate of the switching transistor Q1. The high frequency chosen in this preferred embodiment is 100 kHz.

A preferred embodiment of the modulating signal generator 10, as shown in Figure 2, includes a free running oscillator consisting of a Schmitt inverter I1, a resistance R1 and a capacitance C4 for providing a high frequency pulsed square wave signal on line 16, as illustrated in Figure 3A. The resistance R1 is connected between the input and output of the inverter I1 and the capacitance C4 is connected between the input of the inverter I1 and circuit ground.

The modulating signal generator 10 further includes a differentiating circuit consisting of a capacitance C5 and a resistance R2; an npn transistor Q2; a current limiting resistance R3; a capacitance C6 and a comparator consisting of a high gain amplifier A1.

The square wave signal on line 16 is differentiated by the differentiator circuit C5, R2 to cause the transistor Q2 to be turned on each time there is a positive going transition in the square wave on line 16. The capacitance C6 is discharged each time the transistor Q2 is turned on, but then is charged by the current through the resistance R3 from a DC supply voltage terminal V_C while the transistor Q2 is turned off. As a result, a sawtooth waveform is provided on line 18 to one input terminal of the comparator A1, as shown by the solid line in Figures 3B and 3D.

A low frequency reference signal V_R is applied to the other input terminal of the comparator A1 for comparison with the sawtooth signal on line 18. The frequency of the reference signal V_R is chosen in accordance with what predetermined low frequency the current through the load 12 is to be varied. Typically, the predetermined low frequency is 50 or 60 Hz.

The amplitude of the reference signal V_R varies at the predetermined low frequency. When the reference signal V_R has a relatively high amplitude (as shown in Figure 3B), a pulsed high frequency modulating signal having a relatively short duty cycle (as shown in Figure 3C) is provided on line 14 from the output of the comparator A1 to the gate of the switching transistor Q1 (Figure 1). When the reference signal has a relatively low amplitude (as shown in Figure 3D), a pulsed high frequency modulating signal having a relatively long duty cycle (as shown in Figure 3E) is provided on line 14 from the output of the comparator A1.

The amplitude of the current through the load 12 is proportional to the amount of time that the switching transistor Q1 is turned on, which is in turn proportional to the duty cycle of the pulsed high frequency modulating signal. Accordingly, the current through the load 12 is varied at the predetermined low frequency of the reference signal V_R .

The inductance value of the first inductance coil L1 is chosen to have enough inductance to allow only negligible current to build up when the pulsed modulating signal on line 14 has a minimum discrete duty cycle, and to allow a relatively large current to build up when the pulsed modulating signal on line 14 has a maximum discrete duty cycle. When the current through the first inductance coil L1 is terminated during each pulse upon the switching transistor Q1 being turned off, the stored energy in the two mutually coupled inductance coils L1 and L2 results in a high positive voltage at point 20 on the switching transistor side of the first coil L1. This is commonly known as overshoot. Overshoot is minimized in the current modulator of the present invention by coupling induced energy from the first coil L1 to the second coil L2 and returning the energy received by the second coil L2 back to the power supply side of the load 12 via the diode D2. If overshoot was not minimized, it typically would damage the switching transistor Q1 and the first coil L1. The energy that returned back to the power supply side of the load 12 via the diode D2 reduces the current that must be supplied from the power supply terminal V_s through the diode D1 by an amount equal to the average current through the diode D2.

In the current modulator of Figure 1, when the instantaneous voltage at point 22 on the switching transistor side of the load 12 exceeds the power supply voltage V_s , the diode D2 does not short circuit the load 12 because the inductance coils L1 and L2 are not conductively coupled to each other, whereby there is no DC current path from the point 22 through the diode D2 back to the power supply side of the load 12. As a result, the instantaneous voltage at the point 22 may swing to as much as twice the power supply voltage V_s .

As the switching transistor Q1 is switched on with a short turn-on time, there will be minimum loss in the transistor Q1 during the turn-on time because there is low current in the inductance L1 for a fast step change. If the saturation voltage

on the transistor Q1 is low, the average power lost in the transistor Q1 may be minimized during its "on" time and if the transistor Q1 is turned off with a very short turn-off time, the losses across the transistor Q1 during turn-off may be kept quite small. Therefore, switching at a high frequency is preferred.

5 The coils L1 and L2 have a very low resistance, whereby the heat losses in these coils L1 and L2 are quite small. Typically, the current modulator of Figure 1 will deliver 96 percent of input power into the load with four percent being dissipated in the combination of the coils L1 and L2, the
10 switching transistor Q1 and the diode D2.

A preferred embodiment of the current modulator of the present invention that is particularly adapted for use with a transformer as a load is described with reference to Figures 4, 5 and 6. The load is the primary winding S of the transformer T1
15 is connected between an output terminal V_0 and circuit ground.

20 The current modulator includes first and second high frequency switching devices Q11 and Q12. As in the preferred embodiment of Figure 1, the switching devices Q11 and Q12 are VMOS FET power transistors which are capable of switching at high frequencies, such as 100 kHz.

25 The current modulator of Figure 4 further includes first, second, third and fourth inductance coils L11, L12, L13 and L14, first and second diodes D11 and D12, capacitances C11 and C12 and a modulating signal generator 24.

30 The primary winding P has a center tap 26 that is connected to a DC power supply terminal V_S .

 The first switching transistor Q11 is connected between one side 28 of the primary winding P and circuit ground for varying the current through the primary winding P in response to the first modulating signal applied on line 30 to the gate of the
30 switching transistor Q11 from the modulating signal generator 24.

The first inductance coil L11 is connected between the first transistor Q11 and the one side 28 of the primary winding P.

The second inductance coil L12 is mutually coupled to the first inductance coil L11 for receiving energy induced in the first coil L11 by the current variations. The first and second coils L11, L12 are tightly wound on an air-filled core by a bifilar or preferably a coaxial winding. The first and second coils L11, L12 are conductively isolated from each other.

The first diode D11 is coupled between the second coil L12 and the other side 32 of the primary winding P for transferring the received energy from the second coil L12 through the other side 32 of the primary winding P to the power supply terminal V_S .

The second switching transistor Q12 is connected between the other side 32 of the primary winding P and circuit ground for varying the current through the primary winding P in response to a second modulating signal applied on line 34 to the gate of the second switching transistor Q12 from the modulating signal generator 24.

The third inductance coil L13 is connected between the second transistor Q12 and the other side 32 of the primary winding P.

The fourth inductance coil L14 is mutually coupled to the third inductance coil L13 by the current variations. The third and fourth coils L13, L14 are tightly wound on an air filled core by a bifilar or preferably a coaxial winding. The third and fourth coil are conductively isolated from each other.

The second diode D12 is coupled between the fourth coil L14 and the one side 28 of the primary winding P for transferring the received energy from the fourth coil L14 through the one side 28 of the primary winding P to the power supply terminal V_S .

The modulating signal generator 24 is adapted for applying the first and second modulating signals to the respective gates of the switching transistors Q11 and Q12. The first and second modulating signals are applied in such a manner as to cause only one side of the primary winding P to be connected to circuit ground at any one time.

A preferred embodiment of the modulating signal generator 24, as shown in Figure 5, includes an oscillator circuit consisting of a first hysteresis inverter G1, a resistance R11 connected between the input and the output of the inverter G1 and a capacitance C11 connected between the input of the inverter G1 and circuit ground.

The modulating signal generator 24 further includes a second hysteresis inverter G2 having its input connected to the output of the inverter G1; an input amplifier A2, and resistances R12, R13, R14 and R15. A reference signal terminal V_R is connected through the resistance R12 to the inverting input terminal of the amplifier A2. The inverting input terminal is also connected through the resistance R13 to a power supply terminal V_C . The non-inverting input terminal of the amplifier A2 is connected to circuit ground. The resistance R14 is connected between the inverting input and the output of the amplifier A2. The output of the amplifier A2 is connected through the resistance R15 to the input of the first hysteresis inverter G1.

The oscillator circuit G1, R11, C11 provides a square wave pulsed signal on line 30, as shown in Figure 6A. The inverter G2 inverts the signal on line 30 to provide a complementary square wave pulsed signal on line 34. If the signals on lines 30 and 34 each have the same duty cycle, the average current through the primary winding P of the transformer T1 in the current modulator of Figure 4 will be zero.

When the output of the inverter G1 on line 30 switches high, the capacitance C11 is charged through the resistance R11 to provide a signal at the input terminal 36 of the inverter G1 having a waveform as shown in Figure 6B. When the voltage of the signal at input terminal 36 rises to the upper switching threshold V_2 of the inverter G1, the output of the inverter G1 switches low as shown in Figure 6A. The capacitance C11 is then discharged through the resistance R11 until the voltage of the signal at the input terminal 36 drops to the lower switching threshold V_1 of the inverter G1, at which point, the inverter G1 again switches high.

The duty cycle of the pulsed signal provided on lines 30 and 34 from the respective outputs of the inverters G1 and G2 is varied by varying the rate at which the capacitance C11 is charged or discharged. This is accomplished by varying the current through the resistance R15 to the input terminal 36 of the inverter G1. Such current variation is caused in response to a reference signal having a predetermined low frequency that is applied to the reference signal terminal V_R . The frequency of reference signal is chosen in accordance with what predetermined low frequency the current through the primary winding P of the transformer T1 is to be varied. Typically, the predetermined low frequency is 50 or 60 Hz..

The amplifier A2 inverts the reference signal applied to the terminal V_R and causes a current to be provided through the resistance to R15 the inverter input terminal 36 that either aids or opposes the current through the resistance R11 in charging or discharging the capacitance C11.

When the voltage at the output terminal 38 of the amplifier A2 is negative with respect to the average value of the voltage at the inverter input terminal 36, the capacitance C11 is charged slowly and discharged quickly, as shown in Figure 6C. This causes the first inverter output signal on line 30 to have a long duty cycle, as shown in Figure 6D. Conversely, the pulsed output signal of the second inverter G2 simultaneously has a short duty cycle.

When the voltage at the output terminal 38 of the amplifier A2 is positive with respect to the average value of the voltage at the inverter input terminal 36, the capacitance C11 is charged quickly and discharged slowly, as shown in Figure 6E. This causes the first inverter output signal on line 30 to have a short duty cycle as shown in Figure 6F. Conversely, the pulsed output signal of the second inverter G2 simultaneously has a long duty cycle.

The imbalance in the duty cycles of the pulsed modulating signals applied to the respective gates of the switching transistors Q11 and Q12 causes the average current flow through the primary winding P of the transformer T1 to be other than zero. The amount of current flow through the primary winding P is proportional to the difference between the duty cycles of the pulsed modulating signals applied on lines 30 and 36 to the respective gates of the switching transistors Q1 and Q2.

Current flow through the primary winding P is greater in the direction from the center tap 26 toward the one side 28 when the duty cycle of the pulsed modulating signal on line 30 is greater than the duty cycle of the pulsed modulating signal on line 34.

The variation in the amplitude and direction of current flow through the primary winding P is in response to the variation of instantaneous voltage at the amplifier output terminal 38 in the modulating signal generator 24. Thus by providing a predetermined low frequency reference signal to the reference signal terminal V_R , an output signal having the predetermined low frequency is produced at the output terminal V_0 of the secondary winding of the transformer T1. Accordingly, the current modulator of Figure 4 is particularly useful for providing a low distortion sine wave low frequency output signal.

Basically, the operation and specifics of construction of the respective combinations of the switching transistor Q11, the inductance coils L11, L12 and the diode D11 and the switching transistor Q12, the inductance coils L13, L14 and the diode D12 in the current modulator of Figure 4 are the same as those of the combination of the switching transistor A1, the inductance coils Q1, Q2 and the diode D1 in the current modulator of Figure 1.

A unique feature of the current modulator of Figure 4 is the use of the energy recovery path through the primary winding P to provide additional efficiency. This may be seen as follows: If the two diodes, D11 and D12 had their cathodes connected to the power supply terminal V_s . The received energy from the coil L2 and L4 still would be returned to the power supply. However, when these two diodes D11 and D12 are cross-connected to the opposite sides 28, 32 of the primary winding P, as shown in Figure 4, then the recovered energy flows not only back to the power supply, but returns to the power supply through the opposite non-conducting side of the primary winding, and thereby provides added volt-ampere turns to the transformer T1. Since the recovered energy from the collapsing field of the inductance coils tries to generate a high voltage "inductive kick" that is clipped by diodes D11 and D12, the current through these diodes D11, D12 tends to be relatively constant for different voltages during the energy recovery period.

CLAIMS

1. A current modulator for modulating the current flowing through a load from a DC power supply to circuit ground, comprising

5 a switching device connected between the load and circuit ground for varying the current through the load in response to a modulating signal applied to the switching device;
a first inductance coil connected between the switching device and the load;

10 a second inductance coil mutually coupled to the first coil for receiving energy induced in the first coil by said current variations, the second coil being conductively isolated from the first coil; and

15 a diode coupled between the second coil and the power supply side of the load for transferring the received energy to the power supply side of the load.

2. A current modulator according to claim 1, wherein the switching device is a high frequency switching device.

3. A current modulator according to claim 2, further comprising

means for applying a high frequency pulsed modulating signal to the switching device.

4. A current modulator according to claim 3, wherein the switching device is a MOS semiconductor device.

5. A current modulator according to claim 4, wherein the switching device is a VMOS FET power transistor.

6. A current modulator according to claims 3 or 5, wherein the means for applying the modulating signal to the switching device comprises

first means for generating a high frequency pulsed signal; and

second means for varying the duty cycle of the pulsed signal at a predetermined low frequency to thereby provide the high frequency pulsed modulating signal for varying the current through the load at the predetermined low frequency.

7. A current modulator according to claim 6, wherein the second means is adapted for varying said duty cycle in response to a reference signal having said predetermined low frequency.

8. A current modulator according to claim 3, wherein the inductance coils have an air core.

9. A current modulator for modulating the current flowing through a load to circuit ground from a DC power supply connected to the load, comprising

a first switching device connected between one side of the load and circuit ground for varying the current through the load in response to a first modulating signal applied to the first switching device;

a first inductance coil connected between the first switching device and the one side of the load;

a second inductance coil mutually coupled to the first coil for receiving energy induced in the first coil by said current variations, the second coil being conductively isolated from the first coil;

15 a first diode coupled between the second coil and
the power supply for transferring the received energy from the
second coil to the power supply;

20 a second switching device connected between the other
side of the load and circuit ground for varying the current
through the load in response to a second modulating signal
applied to the second switching device;

a third inductance coil connected between the second
switching device and the other side of the load;

25 a fourth inductance coil mutually coupled to the third
coil for receiving energy induced in the third coil by said
current variations, the fourth coil being conductively isolated
from the third coil;

a second diode coupled between the fourth coil and
the power supply for transferring the received energy from the
fourth coil to the power supply; and

30 means for applying the modulating signals to the
switching devices to cause only one side of the load to be
connected to ground at any one time.

10. A current regulator according to claim 9,
wherein the first diode is coupled between the second
coil and the other side of the load for transferring the
received energy from the second coil through the other side of
5 the load to the power supply; and

wherein the second diode is coupled between the fourth
coil and the one side of the load for transferring the
received energy from the fourth coil through the one side of
the load to the power supply.

11. A current regulator according to claim 10, for use with a load having a center tap, further comprising means for connecting the center tap to the power supply.

12. A current regulator according to claim 10, wherein the switching devices are high frequency switching devices.

13. A current modulator according to claim 12, wherein the switching devices are MOS semiconductor devices.

14. A current modulator according to claim 13, wherein the switching device is a VMOS FET power transistor.

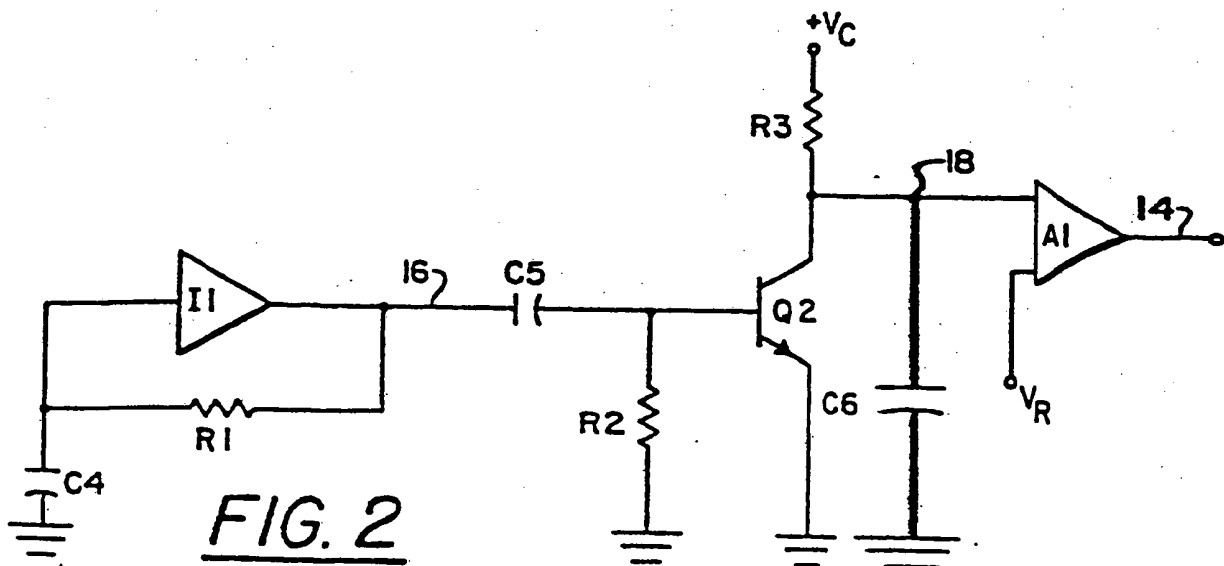
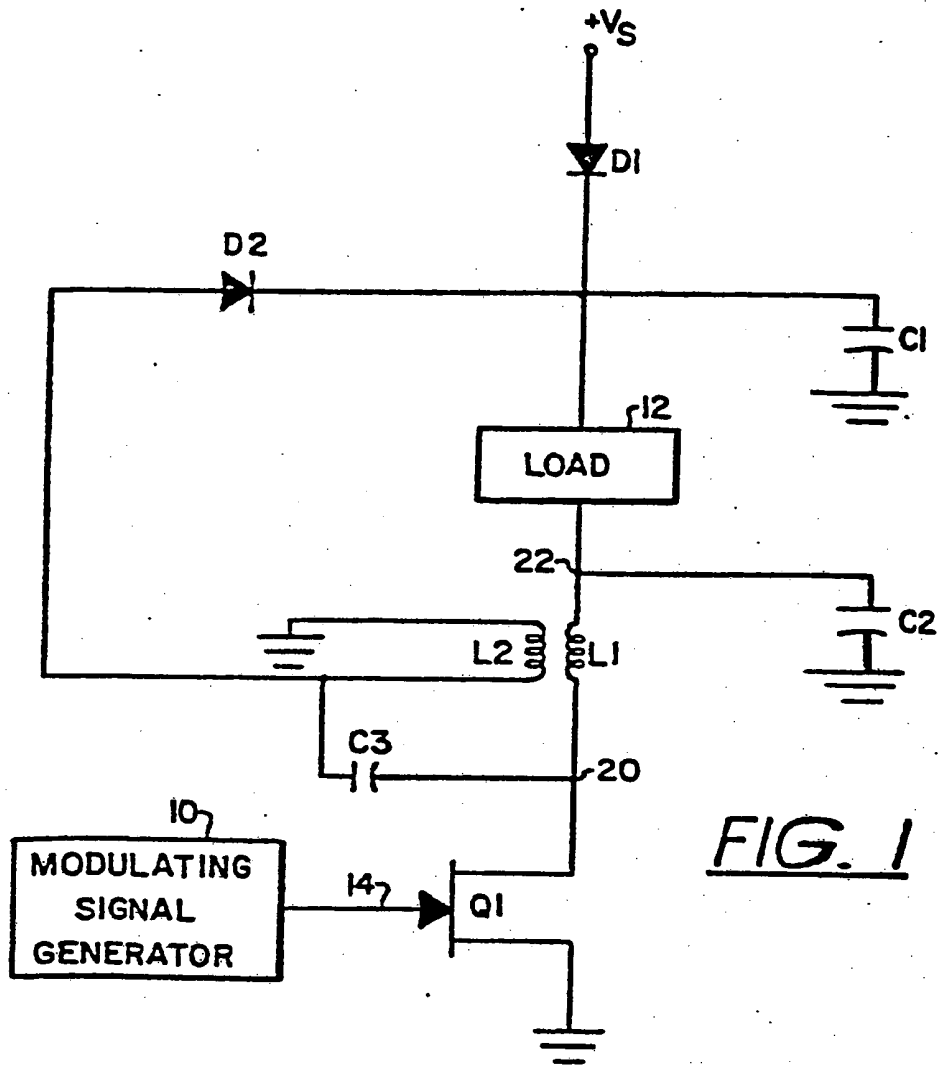
15. A current modulator according to claim 12, wherein the means for applying the modulating signals to the switching devices are adapted for applying high frequency pulsed modulating signals.

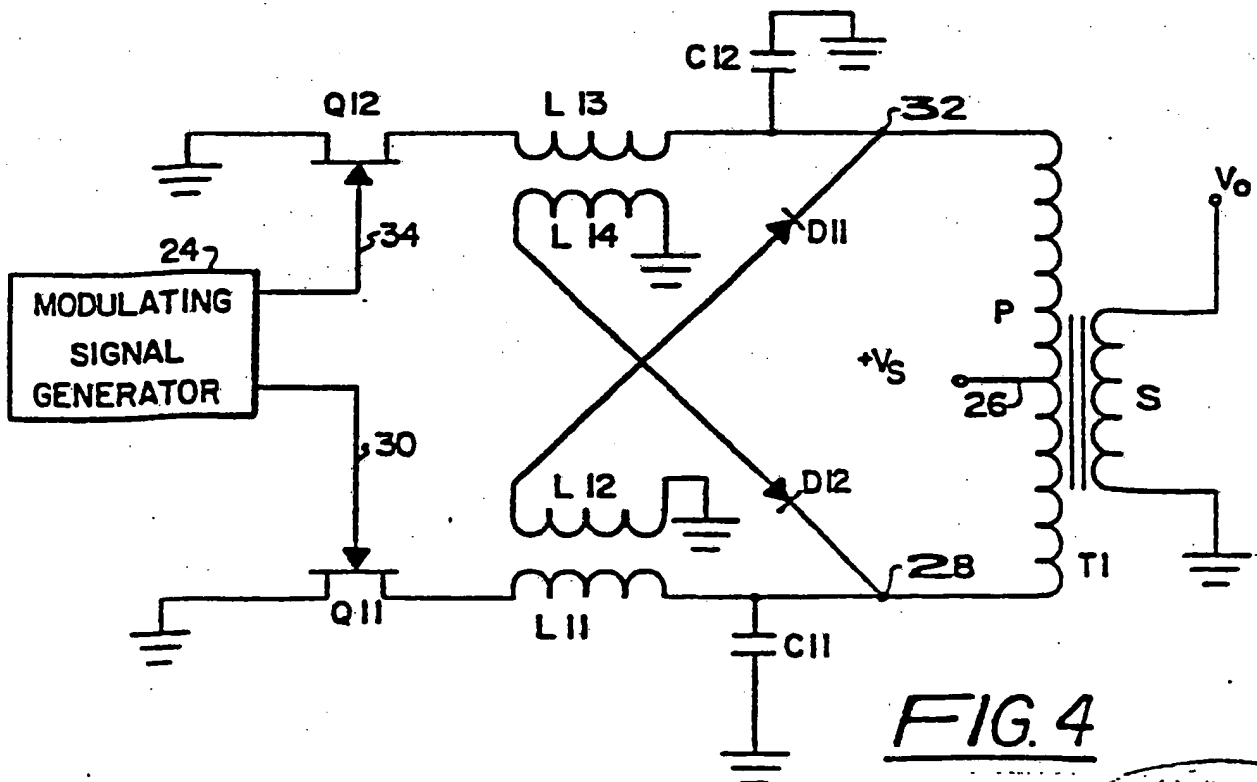
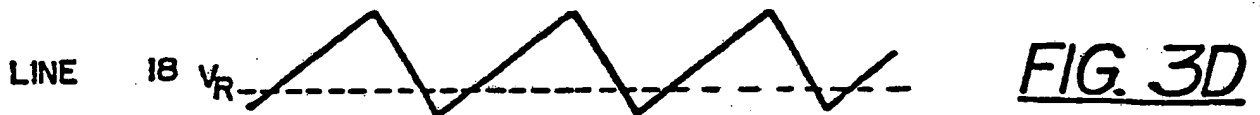
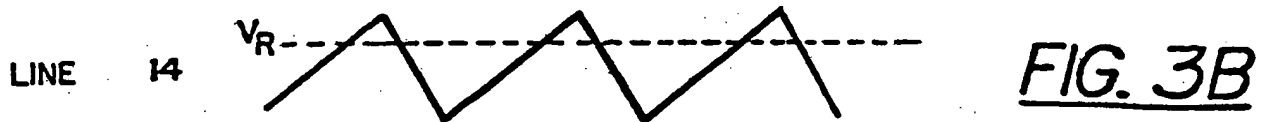
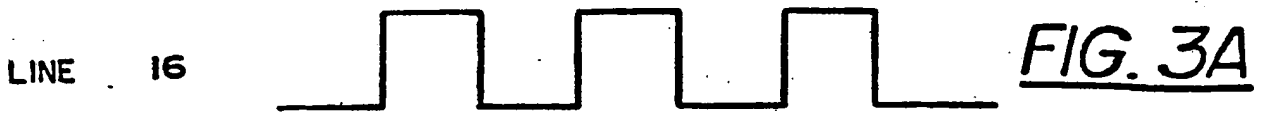
16. A current modulator according to claims 14 or 15, wherein the means for applying the modulating signals to the switching devices comprises

5 a first means for generating first and second high frequency pulsed signals that are complementary to each other; and
second means for varying the duty cycles of the first and second high frequency pulsed signals at a predetermined low frequency to thereby provide the first and second modulating signals for varying the current through the load at the pre-
10 determined low frequency.

17. A current modulator according to claim 16, wherein the second means is adapted for varying said duty cycles in response to a reference signal having said predetermined low frequency.

18. A current modulator according to claim 15, wherein the inductance coils have air cores.





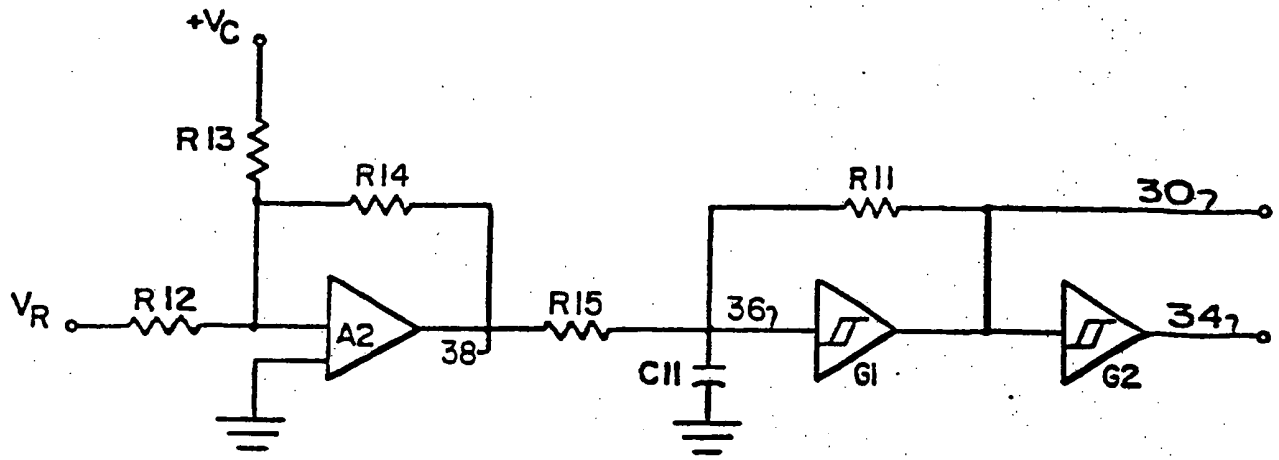


FIG. 5

OUTPUT
LINE 30



FIG. 6A

INPUT
TERMINAL 36

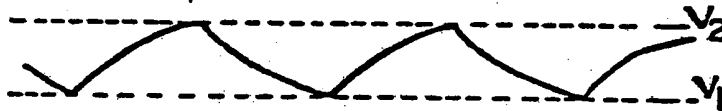


FIG. 6B

INPUT
TERMINAL 36

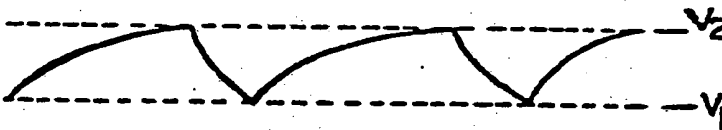


FIG. 6C

OUTPUT
LINE 30

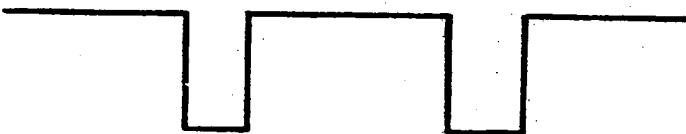


FIG. 6D

INPUT
TERMINAL 36

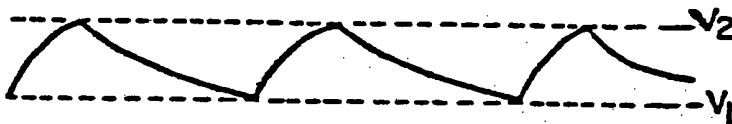


FIG. 6E

OUTPUT
LINE 30



FIG. 6F

INTERNATIONAL SEARCH REPORT

International Application No

PCT/US82/01243

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all) *

According to International Patent Classification (IPC) or to both National Classification and IPC

INT. CL. HO2M 3/335; G05F 1/46

U.S. CL. 363/21, 26

II. FIELDS SEARCHED

Minimum Documentation Searched *

Classification System

Classification Symbols

U.S.

363/18-26, 97-98, 133-134, 139
323/222, 282-290

Documentation Searched other than Minimum Documentation
to the extent that such Documents are included in the Fields Searched *

III. DOCUMENTS CONSIDERED TO BE RELEVANT ¹⁴

Category *	Citation of Document, ¹⁶ with indication, where appropriate, of the relevant passages ¹⁷	Relevant to Claim No. ¹⁸
A	US,A, 2,920,259 Published 5 Jan. 1960, Light	
A	US,A, 4,268,898 Published 19 May 1981, Brown	
A	US,A, 4,021,720 Published 3 May 1977, Linnman	
A,P	US,E, 4,336,587 Published 22 Jun 1982, Boettcher, Jr. et al.	
A	EDN, Volume 25, No. 17, Published 20 Sept. 1980, D. Mele, '100-KHZ DC/DC Converter Uses Fets', See Pages 191-192.	

* Special categories of cited documents: ¹⁵

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"T" later document published on or after the international filing
date or priority date and not in conflict with the application,
but cited to understand the principle or theory underlying
the invention

"X" document of particular relevance

IV. CERTIFICATION

Date of the Actual Completion of the International Search *

Date of Mailing of this International Search Report *

15 Nov. 1982

23 NOV 1982

International Searching Authority ¹

Signature of Authorized Officer ²

